INNOVATIVE GEOTHERMAL POWER PLANTS FIFTEEN YEARS OF EXPERIENCE

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KEYWORD'S

Binary Plants, Organic Rankine Cycle, Geothermal Combined Cycle, Innovative Cycles.

ABSTRACT

The paper describes the technology and field experience with various geothermal binary and combined steam/binary plants for both watci and steam dominated resources having low, moderate or high enthalpy.

The paper focuses on Ormat's approach and 15 years of experience with mention of concepts, prototypes and power plants made by others.

After introducing a thermodynamic approach for the analyses of the cycles, existing operating plants in the U.S., Iceland, Philippines and the Azores are reviewed.

Mention is made of repowering existing steam plants for increased efficiency, iniection support and reduction of environmental impact.

1. INTRODUCTION

- The economics of base load renewable energy geothermal power plants **is** governed mainly by their initial cost. In turn, the initial cost is controlled by the conversion efficiency of the available energy in the geothermal fluid.
- In the effort to improve the efficiency of dry steam and flashed steam plants, many innovative power cycles have been proposed in the last 20 years, some have been tested but only four are in commercial operation, these are: double-flashed steam cycle, the super-critical binary, the cascaded binary and the combined steam and binary.
- Of the 6,000 MW of geothermal plants installed worldwide, most use steam turbines operating on dry steam or steam produced by single flash or double flash. About 300 MW use Ormat binary power plants.
- The operational experience has confirmed the advantages of the binary plants, not only for the low enthalpy water-dominated resources, but also at high enthalpy for aggressive brine or brine with high non condensible gas content. The somewhat higher installed cost of these systems is often justified by environmental and long term resource management considerations.

II. APPROPRIATE THERMO-DYNAMICS FOR GEOTHERMAL POWER PLANT ANALYSIS AND DESIGN

1. What Was Overlooked in Sadi Carnot's Teachings

Carnot was mainly concerned with speculation as to the best possible performance of a heat engine using any working fluid in any possible cycle.

Sadi Carnot, in his famous treatise of 1824 (1), realized that what we call "thermal efficiency" was by no means the most important consideration; his concluding paragraph makes this abundantly clear and is so relevant today that it deserves to be quoted: "the economy of the Combustible is only one of the considerations to be fulfilled in heat engines. In many cases, it is only secondary. It should often give precedence to safety, to strength, to the durability of the engine, to the small space which it must occupy, to small cost of installation, etc... ... to balance them properly against each other, in order to attain the best results by the simplest means".

Carnot also recognized several promising directions in the development of practical heat engines which, if given the attention they deserved when published, could have brought about much sooner the development of both vapor cycle engines using fluids other than steam and of combined cycles. All these are clearly set out by Carnot and were largely overlooked by generations of scientists and engineers until the last few decades **(2)** to (7).

2. Efficiency and Work Ratio

The usual definition of thermal efficiency as the ratio between the net work done by the fluid and the total heat input to the cycle can be misleading in assessing the suitability of a given cycle in a heat engine. **A** concept of paramount importance in evaluating the suitability of a particular cycle for use in a heat engine is that of *work ratio*, which may be defined as the ratio of the net work output of the cycle to the total positive (expansion) work of the cycle.

If there is very little negative work, as in a typical vapor cycle, where only liquid of small specific volume has to be pumped back into the boiler, the work ratio will be nearly unity. By contrast, this ratio is lower in a super critical cycle where a larger portion of the positive work of the turbine is used to drive the feed pump.

Taking into account all these practical implications of work ratio, it can be seen that in many ways the concept of work ratio can be regarded as almost more important than the concept of ideal cycle efficiency.

3. Matching and Optimization in the Design of Heat Engines

The process of design of a geothermal power plant can be considered as one of matching and optimization. We have a source and a sink of heat of certain characteristics and the problem is to match them with the working cycle, match the working cycle with the working fluid, and match the working fluid with the expander. But what matters most is the optimization of the whole system, involving the well-known process of trading-off a loss or gain.

Let **us** now consider, in the case of the geothermal power plant, the various matching processes and their impact not only on efficiency, but also on the environment, on the long-term pressure support and geothermal resource availability.

3.1 Heat Cycle Considerations

In a geothermal power plant, which uses no externally supplied fuel, the effectiveness of the heat usage directly impacts upon the total capital cost of the plant.

Ideally, the most effective way to produce power from the available energy (exergy) in the geothermal fluid is to convert it, in the power cycle, adiabatically and reversibly to the temperature of the cooling medium.

When the source is a single phase (sensible heat) the ideal cycle would have a varying source temperature, being a succession of infinitesimal Carnot cycles. In a sub-critical Rankine cycle thc constant temperature of the evaporation leads to a loss of exergy, however, because of the lower latent heat of vaporization this drawback is lower than in a steam cycle.

This objective of getting closer to the ideal cycle has been aimcd at in proposing the super-critical binary cycle, the different total flow regenerative cycle and in the cascaded binary cycle.

Attempts have also been made to reduce the loss in exergy, due to tne temperature difference in the heat exchanger's, by using dircct contact heat exchange.

When the source is a mixture of steam and brine the most attractive utilization may be achieved by expanding the steam in a steam turbine and utilizing the separated brine as well as the steam in one of the binary cycles described above. This approach provides the maximum project specific benefits, including minimizing environmental impacts (see scction **3.3** below).

When dry steam is available the most effective way is the conventional condensing steam cycle.

To compare the efficiency of the different systems it **is** of course necessary to consider the output net of parasitic's, such as cycle pumps, production pumps, injection pumps, cooling systems and non-condensible gas extraction power consumption.

3.2 Resource Considerations

The decline of production in the Larderello, Geysers and Wairakei fields has focused attention on thc necessity for long-term pressure support by reinjecting as much as possible of geothermal fluid.

In brine's rich in carbonates, avoiding flash by use of secondary loops or of downhole and booster pumps reduces both the fouling of the heat exchanger's and sealing of the injection wells.

3.3 Environmental Considerations

The factors impacting the environment are:

- Non condensible gases (mainly H_2S) released by the steam.
- Discharged fluids such as the separated brine (carrying off heavy metals) and blow down from the cooling towers (chemicals).
- Leak of secondary fluid (especially in case of CFCs).
- Noise and visual impact.

III. REVIEW OF EXPERIMENTAL PLANTS

The cycles are reviewed per status of their reduction to practice. The detailed descriptions of the different systems and the scope of their development are given in the referenced papers.

1. Proposed Systems

- Trilateral cycle - Out of the binary total flow systems (8): the most well conceived is the trilateral cycle (4), which was also partially tested.
- Absorption and Absorption/Regenerative Cycles - of the different cycles proposed (9), the most advanced system is the Kalina cycle (10), which was tested on an energy recovery plant. A demonstration is yet to be made in a geothermal power plant to prove the practicality of the concentration variations, the high pressure of the system, and other factors.

2. Tested Systems

- The total flow steam cycle (bi-phase) (11), although conceptually elcgant and theoretically efficient, did not make it to sustained commercial opcratinn in its prior trials, mainly because of clogging in nozzlcs.
- The direct heat exchanger usage **(12)** encountered serious problems of fouling and excessive hydrocarbon fluid loss.
- Hybrid systems **(13):** this is a complex system combining internal combustion engines with heat recovery from the hot brine and exhaust. The tests have yet to demonstrate the validity of the concept.

IV. INNOVATIVE POWER PLANTS IN COMMERCIAL OPERATION (scc Table 1)

1. Low Enthalpy Resources (100°C to 160°C)

For low enthalpy resources, the binary Organic Rankine System is often utilized to convert thc resource heat to electrical power (Fig. 1). The hot brine or geothermal steam is used as thc heating source for a secondary (organic) fluid, which is the working fluid of the Rankine cycle. Two such plants have been built by Barber Nichols Inc., one by Turbodcn and 17 by Ormat. Some of these units are used in rcpowering existing power plants.

In the early 80's, to increase the power output from a given brine resource by increasing the thermal cycle efficiency, the super critical cycle using isobutane was pioneered by the Ben Holt Company and a cascadc concept was developed by Ormat. The super-critical cycle may bc slightly more efficient than the cascading cycle. but the cascading system has the advantage of lower operating pressures and lowcr parasitic loads (cycle pumps).

At the Ormesa I power plant in Southern California, a three level arrangement was employed resulting in increased efficiency, or power output gain, of about **10%** over that achievable with a parallel arrangement of the OEC units. The gross brine utilization rate of this 166°C resource was 76 kg/kWh. Another **7** such Ormat plants are in operation (Fig. 2) as well as *3* using Bcn Holt super critical technology.

In thc mid 80's Ormat introduced thc Integrated Two Lcvcl Unit (ITLIJ) as a mcans of lowering thc complexity and cost of the plant. Initially an air-cooled plant at Stillwater in Nevada and five other operating projects use ITLU's, which eliminated the need for long brine headers and numerous valves which exist in the previous design.

In all of thc above arrangements, a modular approach was employed so that high plant availability factors of 98% and above were achievable.

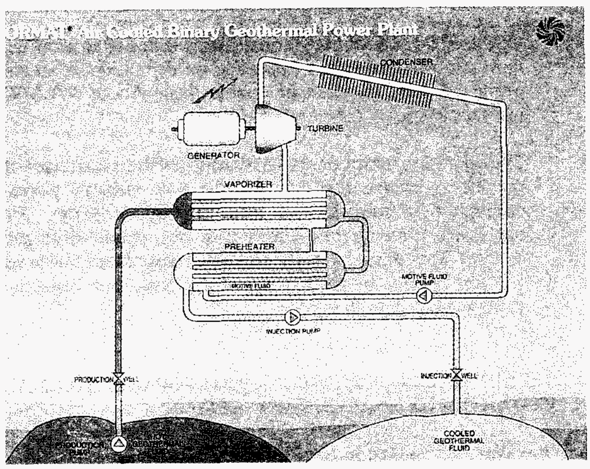

Fig. 1 - Air Cooled Binary Geothermal Power Plant Diagram

Table 1 - Ormat Geothermal Power Plants as of July 1, 1994

TYPE OF PLANT	NO. OF PLANTS	NO OF UNITS	STATUS	YEAR OF INITIAL OPERATION		TOTAL LOGGED UNIT HOURS	MODULE SIZE (MW)		TOTAL CAPACITY (MW)
				Oldest	Newest		Largest	Smallest	
Simple binary	17	70	In commercial operalion	1984	1994	2,600,000	3.5	0.3	98.0
Two-Dhase binary	1	4	In commercial operation		1994	14.000	2 6		5.2
Recuperated binary	1 1	6 5	In commercial operation Under construction		1994	15,000	3.5 3.5	1.3	16.0 17.5
Cascaded binary	5 1	80 7	In commercial operation On order	1986	1993	3,700,000	4.5 4.0	1.2	116.0 28.0
Combined binary/ steam	3 1	17 4	In commercial operation Under construction	1989	1993	540,000	3.0 32.0	1.3	39.0 125.0

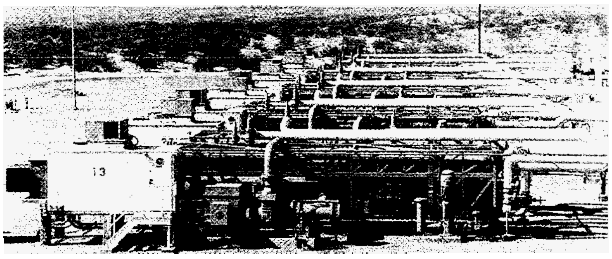

Fig. 2 - Ormesa II Geothermal Power Plant

Fig. 3 - Sao Miguel Geothermal Power Plant

2. Moderate Enthalpy Resources (160°C *to* 190°C)

For moderate enthalpy two-phase resources where the steam quality is between 10 to 30%, the binary plants arc efficient and cost effective. Furthermore, when the geothermal fluid has a high non-condensible gas (NCG) content, even higher efficiency can be obtained than with condensing steam turbines.

This binary two-phase configuration is used in the Sao Miguel power plant in the Azores (Fig. 3). Separated steam containing NCG is introduced in the vaporizer heat exchanger to vaporize the organic fluid. The geothermal condensate at the vaporizer exit is then mixed with the hot separated brine to provide the prehcating medium of the organic fluid (Fig. 4).

Since the onset of silica precipitation is related to its concentration in the brine, dilution of the brine with the condensate effectively lowers the precipitation temperature at which silica crystallizes. This lower temperature added 3.5 MW of heat to the cycle representing 20% of the total heat input. This additional heat is utilized at the same thermal efficiency as the remaining heat due to the nature of the combined steam-brine cycle. Since the cycle efficiency is about 17%, this low temperature heat produces about 600 additional kW.

The second solution to better utilize the resource was the use of a regenerative cycle (15) by the addition of a recuperator heat exchanger between the organic turbine and the air-cooled condenser, since the organic vapor tends to superheat when the vapor is expanded through the turbine. In this case the recuperator reduces the amount of heat that must be added to the cycle from the external source, thereby reducing the amount of brine flow rate required. This results in reduction of about 7% of the total heat input as required to produce the design level of power output.

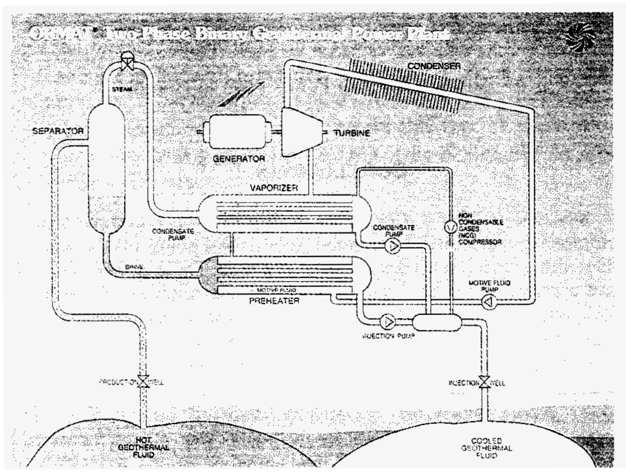

Fig. 4 - Two-phase Binary Power Plant Diagram

3. High Enthalpy Resources (over 190°C)

To best utilize a steam dominated resource Ormat developed a Geothermal Combined Cycle Unit (GCCU) where the steam first flows through a back pressure steam turbine and then is condensed in the organic turbine vaporizer (Fig. 5). The condensate and the brine are used to preheat the organic tluid as in the two-phase binary configuration above.

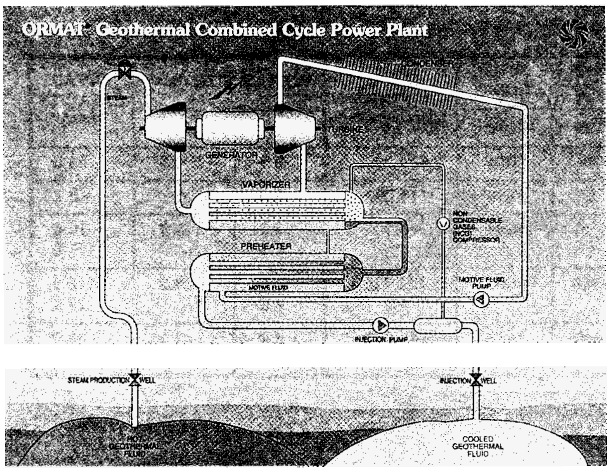

Fig. 5 - Geothermal Combined Cycle Power Plant Diagram

This concept was first used in 1989 in repowering a back pressure steam plant in Iceland, then with ten 3 **MW** GCCU in Hawaii in 1992 (Fig. 6). **A** plant using four 30 **MW** GCCU for a total net capacity of 120 **MW** is now under construction in the Philippines.

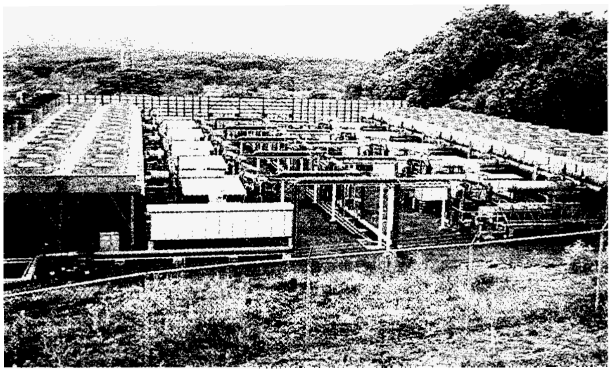

Fig. 6 - Puna Geothermal Power Plant in Hawaii

CONCLUSIONS

As indicated in Table 1, Ormat has designed, installed and put into commercial operation **27** innovative geothermal power plants since 1984, with a total installed capacity of **275 MW.** These power plants have accumulated over **7** million hours of operation as of July 1, 1994, thus demonstrating the maturity of the technology. The Organic Rankine Cycle technology over this 10 year period has evolved to encompass ORMAT's supply and installation of Operating cost effective geothermal steam/binary combined cycle power plants which are specifically designed for geothermal applications. These applications include power plants for new projects with the utilization of low enthalpy (100°C to 160°C), moderate enthalpy (160°C to 190°C) and high enthalpy resources (over 190°C), **as** well as power plants for the repowering of existing geothermal projects.

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